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Holocene fire history in eastern monsoonal region of China and its controls

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ABSTRACT

For the first time we synthesized the fire history for the eastern monsoonal region of China during the Holocene, through the combined analyses of paleofire indices including both charcoal and black carbon records from 14 localities available at present. Our results show that in eastern China fire activity was relatively higher before 9500 cal yr BP, very low between 9500 and 7500 cal yr BP, and evidently increased since 7500 cal yr BP, reaching its maximum at about 2000 cal yr BP. This general pattern of fire activity closely follows the Holocene effective moisture evolution in the eastern monsoonal China at an orbital timescale, i.e. more fires occurred during drier conditions, while less fire occurred during more humid conditions. These results suggest that the fire activity in eastern China were primarily driven by climate changes (i.e., variations of past moisture conditions) and monsoon-related changes in vegetation communities, ultimately forced by the Northern Hemisphere insolation (NHI) on orbital timescales over the Holocene. Our data also show that the fire activity increased concurrently with significant human development from the mid- to late-Holocene, possibly suggesting an intensified trend of human-induced fire activities since about 7500 years ago. Moreover, the fire activity in eastern China closely parallels the atmospheric CO_2 concentration inferred from Antarctica ice-cores. Our synthesis will help to better understand the relationship between fire, climate and human activity at a variety of geographical scales.

1. Introduction

Over the past decade, a surge in the incidence of large, uncontrolled fires has occurred in many regions of the world (for instance, the recent strong forest fires occurring in Southern California, USA, from early October to December in 2017), causing huge economic costs, and meanwhile attracting great attention to the relationships between the fire incidence and anthropogenic global warming. The 2007 Intergovernmental Panel on Climate Change (IPCC) report concluded that global climate change will increase the risk of extreme fire events (IPCC, 2007), however, accurately predicting climate effects on fires requires a full understanding of the causal mechanisms linking climate and fire behavior (Fauria et al., 2011). More complex is that, past, present and future human activities also have affected or will affect fire-climate-vegetation linkages at all temporal and spatial scales (Whitlock et al., 2007; Wang et al., 2013; Marlon et al., 2013). Though fire dynamics and the controls on fire activity at different temporal and spatial scales have been more thoroughly evaluated and synthesized for many regions and paleo-climatic settings (e.g., Power et al., 2008; Daniau et al., 2010; Mooney et al., 2011; Carter et al., 2017; Hawthorne and Mitchell, 2017), there remain many gaps in our knowledge concerning the long-term and broader spatial scale trends in fire regimes for particular regions (e.g., the eastern monsoonal region of China). In particular, examining the relations between fire and its controlling factors in various regions reveals that not all areas follow a same or similar pattern, presumably due to specific local conditions that were either conducive or unfavorable to fire (Hawthorne and Mitchell, 2017). In addition, during recent decades, there have been large changes in fire activity (Marlon et al., 2013; Carter et al., 2017), and in coming decades, many regions may have to face longer fires seasons and more frequent fires as a result of climatic warming (Flannigan et al., 2009). Such changes in fire activity, and the possibility of further changes in an anthropogenic warming world, create great management challenges in many regions. Therefore, in order to better understand the relations between fire regimes (e.g., fire events, frequency, return interval, etc.) and their controlling factors (natural and/or human-induced forcing), it is useful to look at historical data, indicating both the temporal and spatial patterns in fire activity, as well as the long-term relationship between fire, climate, and human impacts.

The eastern monsoonal region of China is the most populated area of the world and is characterized by a long history of human occupation, which has also determined the vegetation structure and its response to environmental fluctuations (Zhao et al., 2009). It is one of the regions of the world noted for early Holocene complex agricultural

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systems and permanent settlements, from which societal changes radiated (Hosner et al., 2016). As a result, the regional fire patterns/regimes during the Holocene in eastern monsoonal China may be very complex, due to the interactions of different controlling factors (i.e., climate and/or human activities). Recently, paleofire studies in eastern monsoonal China, based on charcoal and/or black carbon analysis, have become a focus of paleoenvironmental research (e.g., Zhao et al., 2010; Wang et al., 2013; Tan et al., 2011, 2013; Zhang et al., 2015; Xue et al., 2015; Yin et al., 2016). Although changes in fire activity in some regions of eastern China can be precisely reconstructed (e.g., the high-resolution history of fires occurring in the Daihai Lake region during the Holocene reconstructed by Wang et al., 2013), most paleorecords (e.g., Tan et al., 2011, 2013; Zhang et al., 2015; Xue et al., 2015; Yin et al., 2016) only provide an indication of relative changes in biomass burning due to relatively lower temporal sampling resolution, and these changes can be assumed to reflect changes in fire activity (Daniau et al., 2010; Marlon et al., 2013). Over the recent decade, the general trends of climate changes have been broadly synthesized and discussed in the eastern monsoonal region of China over the Holocene (e.g., Zhao et al., 2009; Wang et al., 2010; Zhang et al., 2011). However, there has been no attempt, to date, to compile and synthesize the paleofire records from site-based studies in the monsoonal region of China to examine the Holocene fire activity at a broader monsoon-influenced regional scale, and the relations between the fire activity and its possible controlling factors.

In this study, we review available paleorecords of past fire activity from the eastern monsoon-influenced region of China to synthesize broad-scale patterns of fire activity at millennial to orbital timescales during the Holocene (from ~11,500 cal yr BP to present). We then exploit existing syntheses of paleoclimate and archaeological data, and compare these results with our composite fire history data to investigate the role of climate and human influence on paleofire in the eastern monsoonal China.

2. Study region

Our focus in this paper is on the eastern monsoon-influenced region of China (Fig. 1). Although there are variations in the mapping of the modern summer monsoon limit in different references, this does not have a significant effect on discussions of past variations in summer monsoon strength (Zhang et al., 2011). Here we use a modern summer monsoon limit across China as shown in Fig. 1 based on Zhao et al. (2009). The whole region exhibits strong seasonal contrasts in temperature and precipitation, typical of monsoonal climates. Air masses from Siberia and Mongolia and north-westerly winds associated with the Siberian High (i.e., the winter monsoon) predominate during the cold season, and south-easterly winds bring warm and wet air from the Indian Ocean and the Pacific Ocean (i.e., the summer monsoon) during the warm season. Under the influence of the monsoon systems, annual precipitation decreases sharply from the southeast to the northwest from > 1800 mm to ca. 400 mm. The sites selected in this study are mainly located in two vegetation zones (i.e., subtropical evergreen and deciduous forest, temperate steppe; Fig. 1) and their transitional zones. Unfortunately, there are no more satisfactory records in other vegetation zones meeting our site-selection criterion (as described below), specifically owing to their limited time span and/or coarse age control.

3. Methods

3.1. Site selection and dataset

Several paleofire records of varying time span and data quality, using different types of quantification techniques (e.g., pollen-slide charcoal counting analysis and black carbon analysis using chemical oxidation pretreatment), are now available in eastern monsoonal China, though some of them have low temporal resolution and/or cover limited time spans. In this study, four criteria were considered for selecting the proxy records from the study region: (1) the proxy records are considered to be direct and unambiguous indicators of fire, such as sediment-charcoal (e.g., Power et al., 2008 and references therein) and black carbon (e.g., Lim and Cachier, 1996; Schmidt and Noack, 2000; Masiello, 2004; Wang et al., 2013), preserved in lake, swamp, peatland, and loess-paleosol sequences; (2) the records should have a reliable chronology (using either AMS ^{14}C or OSL dating methods) with a minimum of 4 dating control points over the Holocene, sufficient to detect long-term changes at millennial to orbital timescales; (3) the record length had to span most of the Holocene (providing at least a continuous fire history of at least 4000 years) without documented depositional hiatus; (4) the temporal resolution of the proxy records had to be maximally 400 yr per sample. Based on the above criteria, a total of 14 lake, peat, and loess-palesol sites were considered in this study; the locations of the sites are shown in Fig. 1 and listed in Table 1. Our site-selection criteria make our dataset a bit different from previously-published reviews of biomass burning changes based on the Global Charcoal Database (GCD; Power et al., 2008; Daniau et al., 2010; Marlon et al., 2016), which were solely based on sedimentary charcoal records widely distributed in the East Asia and adjacent areas. Furthermore, several latest studies published since 2014 (Table 1) included in our dataset are yet not included in the GCD.

3.2. Data treatment

Considering data available at present, different types of data are used in this study (Table 1), including time series of pollen-slide and sieved charcoal from lake, peat, swamp, and loess-paleosol sediment sequences, and black carbon using chemical oxidation pretreatment from lake sediments. Generally, pollen-slide charcoal encompasses large regional source areas, and charcoal series from pollen slides often show an important background component that is interpreted as the regional production of small charcoal fragments (Tinner et al., 1998), while sieving of sediments to select only the large charcoal particles appears to reflect local fire history (Millspaugh and Whitlock, 1995). However, comparison of charcoal series patterns from the pollen-slide and the sieving methods showed that these two series are broadly similar (Carcaillet et al., 2001). Black carbon also can be used to infer trends in broader-scale burning (e.g., Wang et al., 2013). Hence, both charcoal and black carbon records used in our synthesis, to a large extent, could reflect the long-term trends of regional fires. In most cases (11 of 14 sites), the paleofire records reviewed in this study were published on a calendar year timescale, and the data were digitized from original diagrams in these publications using the software Engauge Digitizer (Mark et al., 2017). For those sites (numbering S6, N6, N7) which only provided dates and corresponding depths, age-depth models were based on linear interpolation between adjacent pairs of dates. As the temporal resolution of the data ranges widely, from decades to centennial, here we mainly focus on the long-term trend in fire activity at a regional (sub-continental) scale over the Holocene. Furthermore, as values of charcoal and black carbon records vary greatly from site to site, and are not directly comparable, all original data had to be uniformly normalized to enable a broad-scale view of fire activity. Here, the original data of each site was normalized following the method used by Carcaillet and Richard (2000), and Carcaillet et al. (2002), as follows:

$$\mathrm{NFAI} = (X_\mathrm{i} - X_\mathrm{m})/X_\mathrm{s} \tag{1}$$

where NFAI is the normalized value (i.e., normalized fire activity index), X_i are original values of charcoal or black carbon records, X_m and X_s represent the mean and standard deviation of individual time series at each site, respectively. As explained by Gil-Romera et al. (2010), data normalization allows various series to be assessed using a comparable scale for all sequences, reducing the variability due to sedimentation rate, vegetation type, catchment physiography, or site-

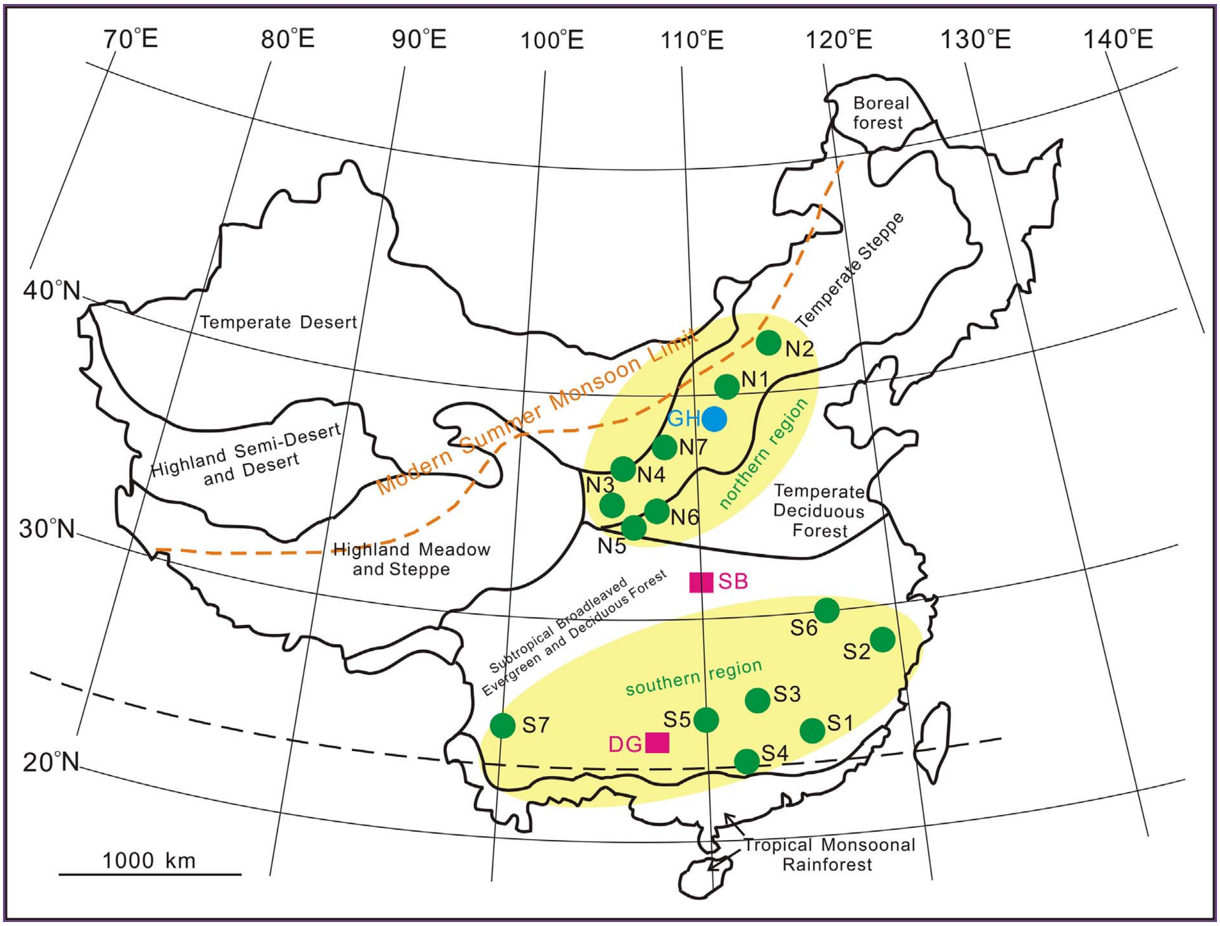

Fig. 1. Sites with paleofire records reviewed in this study (green dots) and vegetation map of China showing major biomes (after Zhao et al., 2009). The sites follows the numbering used in Table 1 (see Table 1 for site information and references). The 14 sites are spatially separated into two groups, i.e., southern region (including S1–S7) and northern region (including N1–N7), with the Qinling Mountains–Huaihe River as the boundary. Other sites referred in the text are also shown, including Sanbao Cave (SB; Dong et al., 2010), Dongge Cave (DG; Dykoski et al., 2005) and Gonghai Lake (GH; Chen et al., 2015). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1
Summary of sites and paleofire indices used in this study.

No	Site name	Type of archives	Time Span (cal yr BP)	Temporal resolution (yr/per sample)	Dating method and number of date	Quantification Techniques	References
N1	Daihai, DH99	Lake core	0–11,700	~100	AMS ^{14}C, 8	BCMSR	Wang et al., 2013
N2	Hulun Nuur, HLNR	Lake core	0–6300	~100	AMS ^{14}C, 9	CHAR	Yin et al., 2016
N3	Tianchi, GAS07-1	Lake core	0–6200	~85	AMS ^{14}C, 19	CCn	Zhao et al., 2010
N4	Loess Plateau, CCY	Loess-paleosol section	0–12,580	~260	OSL, 7	CHAR	Tan et al., 2013
N5	Loess Plateau, LJY	Loess-paleosol section	0–11,900	~200	OSL, 10	CHAR	Tan et al., 2013
N6	Guanzhong Basin, WLP	Loess-paleosol section	0–11,500	~120	OSL, 7	CCn	Tan et al., 2011
N7	Loess Plateau, MJY-A	Loess-paleosol section	0–11,500	~100	OSL, 4	CCn	Tan et al., 2011
S1	Dingnan, Dahu	Peat section	0–10,000	~200	AMS ^{14}C, 7	CCt	Dodson et al., 2006
S2	Wuyi Mts, LTY	Peat section	0–8200	~260	AMS ^{14}C, 5	CHAR	Ma et al., 2016a
S3	Jinggang Mts, SMP	Swamp core	0–4000	~90	AMS ^{14}C, 4	CHAR	Huang et al., 2014
S4	Gaoyao County, GY1	Peat section	0–5000	~60	AMS ^{14}C, 4	CHAR	Ma et al., 2016b
S5	Gutian, GT2	Peat section	0–10,000	~360	AMS ^{14}C, 5	CHAR	Ma et al., 2016a, 2016b
S6	Chaohu, CH-1	Lake core	0–9400	~100	AMS ^{14}C, 7	CCn	Wu et al., 2008
S7	Tengchongqing-hai	Lake core	0–18,500	~100	AMS ^{14}C, 17	BCt	Zhang et al., 2015

Both charcoal and/or black carbon records are interpreted as fire indicators and hence were used to reconstruct fire history by the original authors (see details in the original references). Abbreviation: BCMSR: black carbon mass sedimentation rate; CHAR: charcoal accumulation rate; CCn: charcoal concentration; CCt: charcoal content; BCt: black carbon content.

specific processes. Although information about the fire activity provided from different sources may be different, changes in charcoal and/or black carbon abundance are adequate to resolve periods of relatively higher and lower fire activity (as fully discussed in the original references and references therein). It is also important to note that this assumption is roughly acceptable even for analyses of low temporal

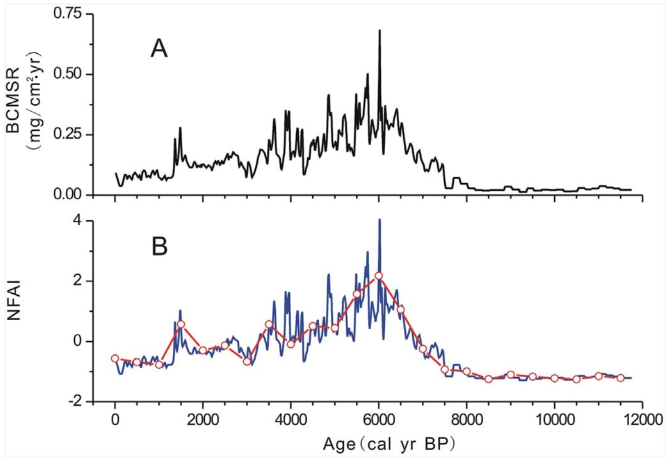

Fig. 2. Comparison of (A) the original BCMSR time series from Daihai Lake (Wang et al., 2013) and (B) the normalized series processed in this study. In (B), the blue line is normalized based on the original data, and the red line with symbol is interpolated at 500-year intervals. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

resolution. According the normalization method, the NFAI will not distort the original patterns of fire activity variation at individual sites (see Fig. 2 for Daihai Lake as an example), and can be used as a dimensionless index of fire activity change, such that larger values represent more fires and lower values indicate less fire.

We resampled each of the normalized individual time series with a 500-year interval (this interval was chosen to avoid identifying single anomalous fire events, such as resulting from post-fire charcoal runoff and secondary accumulation following erosive events, as well as to allow synthesis of sites with lower sampling resolution; Feurdean et al., 2012) for all 14 sites using the software Origin 7.0, and then synthesized them into a single curve by averaging all values at each individual time series to generate the composite fire activity record, following the method as described in Zhang et al. (2011). Notably, the procedure used here assumes that variations of fire activity from each site are equally sensitive to climate change and/or human impacts, and equally well dated, although in reality, some records are better dated than others, some have coarser resolution, and some might have lower sensitivity to climate change or human activity than others. Nonetheless, these synthesized reconstructions help us document and understand variations of fire activity. Furthermore, to investigate the role of climate and/or human influence on paleofire activity in the eastern monsoonal China, we compared our synthesized fire records with many published records (e.g., Dykoski et al., 2005; Zhao et al., 2009; Zhang et al., 2011; Chen et al., 2015; Hosner et al., 2016), which were selected as indicators of climate change or human activity, and examined the correlation coefficients between them using the software DPS v7.05 (Tang and Zhang, 2013).

4. Results

Charcoal and/or black carbon records of changes in fire activity during part or all of the Holocene in eastern monsoonal China are available from 14 sites (Table 1). These sites are spatially clustered into two groups (Fig. 1), 7 sites (N1-N7) from northern China and 7 sites (S1-S7) from southern China, which experience different climate and vegetation settings from one another. Although the geographic coverage of sites in our dataset is uneven, these available data do provide an acceptable coverage of the range of climates and vegetation types in eastern monsoonal China.

The normalized fire activity changes at individual sites from southern and northern regions of China show different temporal and spatial patterns during the Holocene (Fig. 3). For simplicity, we separate the Holocene into three intervals, including the early (~11,500–8000 cal yr BP; EH), middle (8000–4000 cal yr BP; MH), and late (4000–0 cal yr BP; LH) Holocene. On the whole, results from 7 sites in the southern region of China show similar trends in fire activity during the Holocene (Fig. 3A), namely more fires occurred during the LH, while less fire occurred during the MH and EH. In the northern region of China, the trend in fire activity from the 7 sites is more complicated (Fig. 3B), as fire activity varies greatly between sites. Specifically, the records from two sites (N1, N2) in North China show relatively higher levels of fire activity during the MH, while 3 sites (N3-N5) from the Loess Plateau and surrounding areas show relatively lower levels of fire activity during the MH. The record from site N6 in the Guanzhong Basin shows that more fires occurred during both the EH and late-LH, while the record from site N7 in the middle of the Loess Plateau shows relatively higher levels in the EH and early-MH, and then overall decline until late in the LH. Overall, the synthesized fire activity in southern China does not vary synchronously with that of northern China (Fig. 3C and D); the fire activity of northern China varies more frequently than that of southern region of China at millennial time scales. Nonetheless, both of them show relatively higher levels of fire activity during the LH than the MH and EH.

In order to summarize a broad scale history of fire activity during the Holocene, we constructed composite fire activity records for eastern monsoonal China as a whole (Fig. 4A). Overall, the general pattern of fire history in eastern China (Fig. 4A) shows relatively lower levels of fire activity during the EH and MH, and a gradual increase in fire activity from the MH to LH. There are three intervals with relatively higher levels of fire activity during the last 11,500 years. The first occurs between ~11,500 and 10,000 cal yr BP, the second between 7000 and 5000 cal yr BP, while the third comprises a gradual rise in fire activity occurs from the MH to LH across eastern monsoonal China, reaching a maximum at about 2000 cal yr BP. The lowest fire activity is between ~9500–7500 cal yr BP, characterized by a very low fire activity index. In the last 4000 years, fire activity has maintained at a relatively higher level, and the period between 2500 and 1000 cal yr BP appears, on average to be the period of maximum fire activity in eastern monsoonal China.

Furthermore, we compared our composite fire reconstructions with synthesized effective moisture evolutions based on pollen records (Zhao et al., 2009), synthesized moisture index based on $\delta^{18}O_{carb}$ records from lake sediments (Zhang et al., 2011), speleothem record from Dongge Cave (Dykoski et al., 2005), paleoprecipitation reconstruction based on pollen assemblages from Gonghai Lake (Chen et al., 2015), density average estimates for the archaeological sites and estimates of population of China (Hosner et al., 2016) (Figs. 4 and 5), and examined the correlation coefficients between them (Table 2). The results show that the synthesized fire reconstructions in eastern monsoonal China are well correlated with the other records (Figs. 4 and 5; Table 2).

5. Discussion

5.1. Climate and archaeological contexts of Holocene fire activity in eastern monsoonal China

In recent years, climatic variations in the East Asian summer monsoon (EASM)-influenced region of China during the Holocene have been extensively studied based on proxy data obtained from various paleorecords. There also have been several attempts to generalize the long-term trend of Holocene history of the EASM by compiling and synthesizing published paleorecords that are widely distributed in China (e.g., An et al., 2000; He et al., 2004; Herzschuh, 2006; Zhao et al., 2009; Wang et al., 2010; Zhang et al., 2011). These syntheses, however, have displayed partially inconsistent trends and thus have produced contradictory histories. To date, the Holocene evolution of EASM intensity is still debated (e.g., Liu et al., 2015; Rao et al., 2016). In order to better understand the causal links between fire activity and

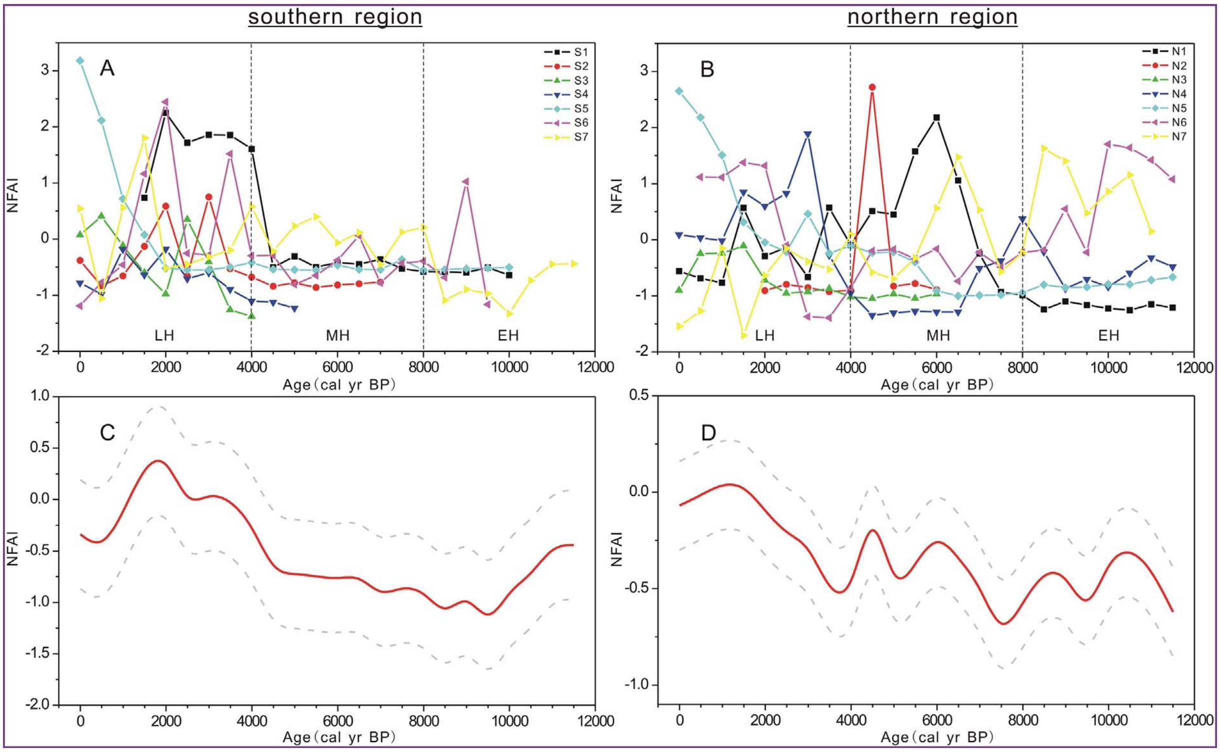

Fig. 3. Normalized fire activity indices at individual sites (A, B) and synthesized fire activity trends (C, D) for the southern region and northern region, respectively. All series are interpolated at 500-year intervals. The dashed lines in (C) and (D) indicate standard errors for each reconstruction.

climate, here we briefly review and summarize the general trend of Holocene climate changes in eastern monsoonal China.

The Holocene climatic variations in the EASM area on millennial or orbital timescales have been robustly ascribed to orbitally-induced changes in solar insolation and subsequent shifts in the position of the Intertropical Convergence Zone (e.g. Wang et al., 2005). During the last decade, numerous high-resolution $\delta^{18}O$ records from stalagmites in monsoonal China have been widely used as indicators of the EASM intensity, due to their precise absolute chronology. Although the paleoenvironmental significance of the Chinese stalagmite $\delta^{18}O$ records has been challenged by recent studies (e.g., Liu et al., 2015 and references therein), variations in stalagmite $\delta^{18}O$ records can still be used as a precipitation or moisture proxy, and therefore be used to infer the summer monsoon intensity in the East Asian region (Cheng et al., 2016): strong summer monsoon and weak summer monsoon can be inferred from low and high $\delta^{18}O$ values, respectively, consistent with results from theoretical and empirical studies. For example, the known Dongge Cave and Sanbao Cave $\delta^{18}O$ records from eastern monsoonal China (Fig. 4E and F), which have been cited as compelling evidence for variations in EASM intensity, exhibit notable evidence of a long-term mid-Holocene weakening of the summer monsoon (Dykoski et al., 2005; Wang et al., 2005; Dong et al., 2010). The interval of most negative $\delta^{18}O$ values in the EH and early-MH, is widely regarded as corresponding to strong EASM intensity thus leading to higher levels of associated precipitation, while less negative $\delta^{18}O$ values from the late-MH to LH are used to infer weak EASM intensity associated with lower levels of precipitation. These variations in the Holocene EASM are supported by the $\delta^{18}O_{carb}$-based integration synthesized from 10 lacustrine records reviewed by Zhang et al. (2011) (Fig. 4D), and the climate pattern inferred from fossil pollen records in eastern monsoonal China (Fig. 4B; Zhao et al., 2009) also generally correlates with this history of Holocene EASM intensity. Based on a comprehensive synthesis of pollen records from 31 sites in the East Asian monsoonal area, Zhao et al. (2009) concluded that environmental moisture levels remained relatively low during the first two millennial of the Holocene until ca. 9500 cal yr BP (about 1000 years later behind the summer monsoon maximum as indicated by $\delta^{18}O$ records from Dongge and Sanbao caves), after which they reached a maximum between 9500 and 6000 cal yr BP (Fig. 4B). Although reconstructions derived from different proxies yield slightly different estimates for the long-term trend of variations in Holocene EASM intensity, these generally overlap during the period of 9000–6000 cal yr BP, strongly suggesting that the Holocene optimum (as defined by peak EASM precipitation) occurred sometime during the EH to MH. Nevertheless, spatial differences in Holocene precipitation for the southern and northern region of eastern monsoonal China have become a focus of recent studies, and exhibit contradictory results in some references (e.g., Liu et al., 2015; Liu et al., 2014; Rao et al., 2016). It is essential that more high-quality paleo-precipitation records are recovered and that model simulations are carried out in order to shed light on the spatial pattern of precipitation variability during the Holocene in eastern monsoonal China (Liu et al., 2015).

Since individual paleoclimate records obtained from specific sites may not be comprehensively representative of larger regions, and apparent inconsistencies exist in the synthesis of Holocene precipitation variations from different kinds of indices for the southern and northern region of eastern monsoonal China (e.g., Liu et al., 2015; Liu et al., 2014; Rao et al., 2016), in the present study we selected the synthesized reconstructions of Holocene effective moisture evolution uniformly based on pollen records (Zhao et al., 2009) for the monsoonal region of China as a whole (Fig. 4B), the tropical evergreen and deciduous forest region (Fig. 5C) and the temperate steppe region (Fig. 5F), to represent the moisture conditions in the whole study region and sub-regions (i.e., southern region and northern region), respectively. These pollen-based reconstructions provide the climate context of fire activity for each region. In addition, cave (Fig. 5A; Dykoski et al., 2005) and lacustrine (Fig. 5D; Chen et al., 2015) records from individual sites complement these syntheses and were compared as additional climate background for the southern and northern regions of eastern monsoonal China, respectively.

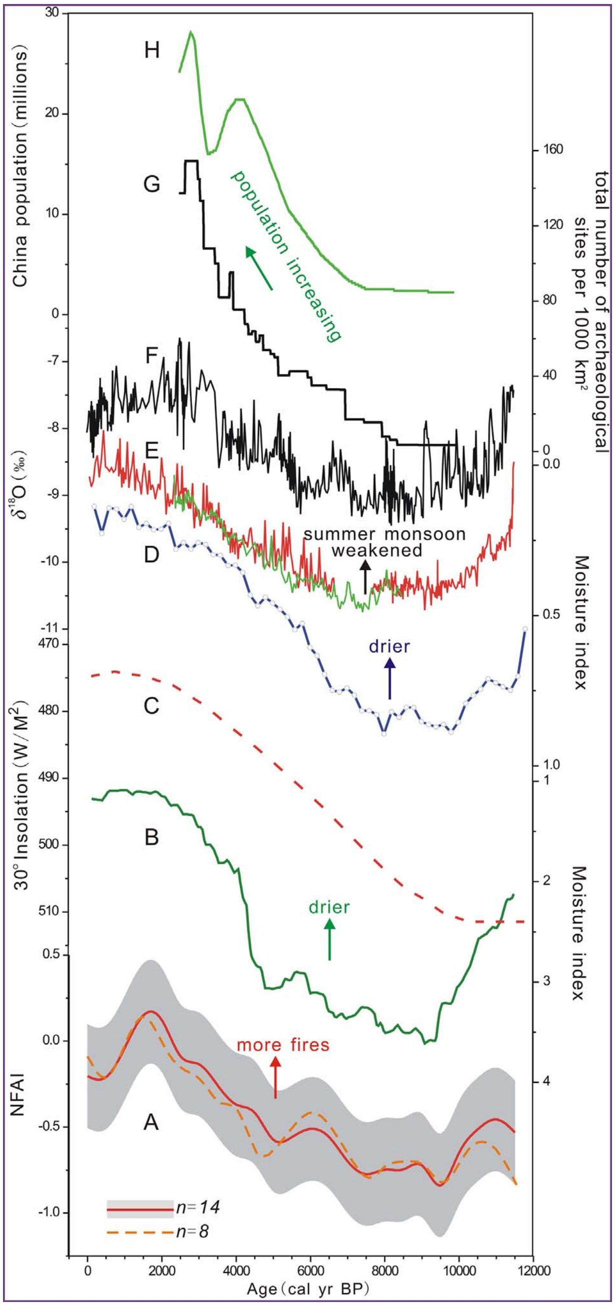

Fig. 4. Synthesized fire activity trends with shadow area as standard errors in eastern monsoonal China (A; this study), and comparison with the other records, including synthesized Holocene effective moisture evolution in the monsoon-influenced region of China based on pollen records (B; Zhao et al., 2009), summer insolation for 30°N (C; Berger and Loutre, 1991), synthesized moisture index based on $\delta^{18}O_{carb}$ records from lake sediments (D; Zhang et al., 2011), $\delta^{18}O$ values in speleothem records from Sanbao Cave (E; Dong et al., 2010) and Dongge Cave (F; Dykoski et al., 2005), density average estimates for the archaeological sites (G) and population (H) in China (Hosner et al., 2016). For comparison, the synthesized fire history reconstruction based on 8 sites with record length longer than 10 ka (this study) is also shown in panel (A) with a dashed line (in orange), nearly identical to the synthesized reconstruction based on all 14 sites (in red). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Moreover, humans can affect fire patterns. Archaeological and ethnographic evidence indicates myriad uses of fire, including burning for food and resource procurement, warfare, travel, and clearance of pests and disease vectors in a variety of environments (e.g., grasslands, woodlands, and forests) (e.g., Mooney et al., 2011; Feurdean et al., 2012; Marlon et al., 2013). The comparison of our synthesized fire history data with the most recent dataset of archaeological sites and population estimates of China (Figs. 4 and 5; Hosner et al., 2016) was used to assess potential correlations between population growth and migrations and fire activity over the Holocene. An increase in the number of archaeological sites is normally interpreted as indicating population growth and growing pressure on the surrounding area (e.g., Wang et al., 2014; Hosner et al., 2016; and references therein). Although estimates of population and the number of archaeological sites may not be adequate proxies for the great diversity of human uses of fire during the Holocene, such complexity should not preclude analyses of available data on changes in population, climate, and fire activity. Rather, such data can provide important insights into human-fire-climate dynamics as well as constraints on those dynamics (Marlon et al., 2013).

5.2. Regional comparison and linkages of fire activity, climate change, and human influence in eastern monsoonal China over the Holocene

Climate changes will influence fire regimes both directly (through influencing lightning ignition, fuel moisture, and the prevalence of fire weather) and indirectly (through changes in vegetation type and productivity) (Power et al., 2008; Daniau et al., 2010; Marlon et al., 2013). In fact, these interactions between climate, vegetation and fire regimes are very complex, and can be difficult to disentangle under modern conditions when fires are severely disrupted by human activities. However, examining long-term changes (on geological timescales) in fire activity can provide an opportunity to distinguish the effects of climate, vegetation, and human influence, especially during intervals when human influence was negligible or nonexistent (Daniau et al., 2010). Here, we explore the relationship between fire activity and changes in climate and human activities in eastern monsoonal China, by comparing fire history with synthesized climate proxy records and archaeological data available at present.

There are several recent examinations of long-term changes in fire activity and their relationships with climate changes and human activities (e.g., Iglesias and Whitlock, 2014; Iglesias et al., 2016; Kauffmann et al., 2016; Hawthorne and Mitchell, 2017; Blarquez et al., 2018). These permit wide insights into both the temporal patterns and spatial variations in fire regimes. To date, there exists no synthesis aimed specifically at reconstruction of Holocene fire activity in the eastern monsoonal region of China. Based on numerous existing sedimentary charcoal records, Power et al. (2008) reported a complex pattern of past global fire regimes at sub-continental to global scales. They found that fire activity in Eastern Asia area (25°–60°N, 90–150°E) was relatively higher in the EH (~12,000–7500 cal yr BP), low during the MH (7500–4000 cal yr BP), and increased again over the last 4000 years (see Fig. 5 in Power et al., 2008). More recently, Marlon et al. (2013) have also summarized the long-term history of Holocene fire activity in the Asian monsoon area (10°–45°N, 65°–150°E), and found that fire activity was relatively higher during the EH, reached a minimum at about 8000 cal yr BP, and increased gradually from 8000 cal yr BP until it reached a maximum at about 2000 cal yr BP, and has declined since then (see Fig. 6C in Marlon et al., 2013). Although the target areas of these two syntheses certainly differ, both agree that fire activity was relatively higher in the EH, lower in the MH and increased over the LH in Eastern Asia (25°–60°N, 90–150°E) or the Asian monsoon area (10°–45°N, 65°–150°E). The temporal trends in fire activity synthesized from 14 sites in the present study (Fig. 4A) are largely consistent with these temporal trends as described above, though the datasets of the individual reconstructions are slightly different. Moreover, most sub-continental reconstructions of biomass burning indicate low fire activity during the EH but increasing fire activity from the MH to LH (e.g., Carcaillet et al., 2002; Marlon et al., 2013).

Sources of ignition and factors influencing fire activity are mainly natural (i.e., volcanic activity, lightning) or anthropogenic (e.g., campfires). As within the monsoonal region of China there were

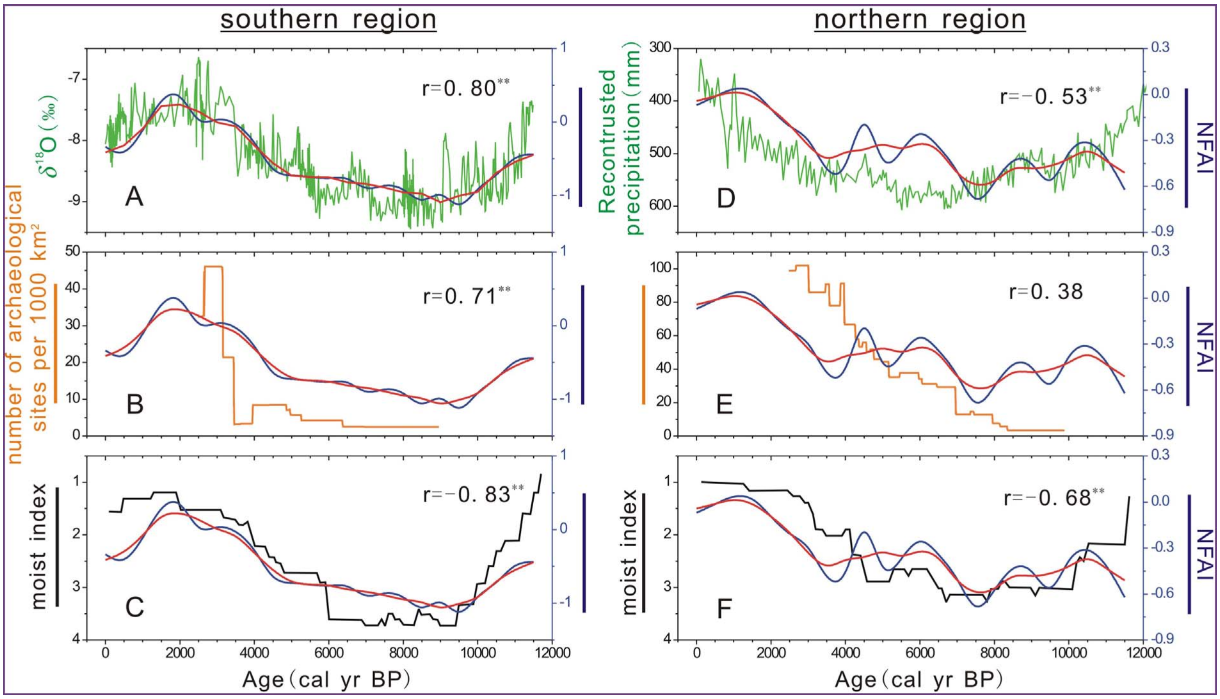

Fig. 5. Synthesized fire activity for southern region (A-C) and northern region (D-F) (this study; blue and red lines indicating a 500-year and a 1000-year smoothing curve, respectively), and comparison with other data. The other data include the δ18O values in speleothem record from Dongge Cave (A; Dykoski et al., 2005), density average estimates for the archaeological sites in southern (B) and northern (E) regions of China (Hosner et al., 2016), synthesized effective moisture in the subtropical evergreen forest area (C) and temperate steppe area (F) (Zhao et al., 2009), paleoprecipitation reconstruction from Gonghai Lake (D; Chen et al., 2015). (A) and (C) are used as indicators of precipitation (or moisture) for southern China; (D) and (F) are used as indicators of precipitation (or moisture) for northern China; (B) and (E) represent potential human impacts for southern and northern China, respectively. "r" in each panel is the correlation coefficient and ** indicates a significant correlation at the 0.01 level. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 2
Statistical correlation between synthesized fire activity and the other paleorecords.

	X1	*X2*	*X3*	*X4*	*X5*	*X6*	*X7*
X1	1						
X2	−0.90**	1					
X3	−0.87**	0.90**	1				
X4	0.81**	−0.84**	−0.77**	1			
X5	−0.49*	0.66**	0.47**	−0.49**	1		
X6	0.93**	−0.95**	−0.94**	0.90**	−0.23	1	
X7	0.89**	−0.90**	−0.97**	0.91**	−0.29	0.94**	1

X1-Synthesized fire activity index for the whole eastern monsoonal region (this study); *X2*- synthesized effective moisture based on pollen records (Zhao et al., 2009); *X3*-synthesized moisture index based on $\delta^{18}O_{carb}$ records from lake sediments (Zhang et al., 2011); *X4*-δ^{18}O values in speleothem record from Dongge Cave (Dykoski et al., 2005); *X5*-paleoprecipitation reconstruction based on pollen assemblages from Gonghai Lake (Chen et al., 2015); *X6*-density average estimates for the archaeological sites (Hosner et al., 2016); *X7*-estimates of population (Hosner et al., 2016). Each series is interpolated and calculated at 500-year intervals.

* Correlation is significant at the 0.05 level.

** Correlation is significant at the 0.01 level.

virtually no volcanoes recorded during the Holocene, lightning, which is a weather-driven phenomenon and an important component of the climate, was the dominant factor in the study area. Since both natural and anthropogenic sources require sufficiently dry fuel, ignition of fire is ultimately controlled by climate (Fauria et al., 2011): fuel must be sufficiently dry for ignition to occur. Our data show that, the fire history reconstructed for the eastern monsoonal region of China at an orbital timescale closely follows the variations of the other records (Fig. 4). Fig. 4 shows the marked similarity between the long-term trends in fire history (Fig. 4A), synthesized effective moisture evolution (Fig. 4B and D), several stalagmite δ^{18}O records of precipitation variations (Fig. 4E and F), and the NHI curve (Fig. 4C), together with high correlation coefficients between the individual records (Table 2). Moreover, fire history reconstructed for southern and northern regions of China also exhibits very similar long-term trends to relevant paleorecords representing climate changes in each sub-region (Fig. 5). As discussed above, Holocene moisture evolution in the monsoonal region of China consists primarily of a relatively drier climate at the beginning of the EH (before ~10,000 cal yr BP), a more humid climate during the early and middle Holocene (~9500–5000 cal yr BP) and a drier climate towards the LH (e.g., Zhao et al., 2009; Zhang et al., 2011). Compared to this pattern of moisture evolution in eastern monsoonal China, fire history synthesized here was overall higher during the early part of the EH, lower during the latter part of the EH and the MH, and increased towards the late Holocene, synchronously corresponding to the concurrent moisture conditions (i.e., more fires during drier conditions, while less fire during more humid conditions). Numerous studies have indicated that orbital forcing may have played major roles in Asian monsoon climate systems throughout geological history, and that Asian summer monsoon strength (leading to high or low levels of associated precipitation) has been driven by the NHI since the early Holocene (e.g., Wang et al., 2005; Herzschuh, 2006; Cheng et al., 2016). Thus, our results clearly demonstrate that fire activity in eastern monsoonal China was primarily driven by climate changes, i.e., variations of past moisture conditions, and then climate-related vegetation changes, ultimately forced by the NHI on orbital timescales over the Holocene. However, the relationship between climate and fire activity in the eastern monsoonal region of China appears to be different from that at a global scale (i.e., high fire activity occurred during warm interstadials or interglacials, and low fire activity occurred during cold stadials or glacials; Daniau et al., 2010). Daniau et al. (2010) considered that the overall reduction in biomass was a sever constraint on fire regimes during the glacial at a global scale, i.e., cold and dry climate influenced plant biomass and therefore available fuel for fire was limited. As in the eastern monsoonal China, vegetation changes are mainly controlled by

the monsoon-related precipitation, and their response to climate changes is very sensitive and rapid (Xue et al., 2015). That is, the strengthened EASM intensity may have caused an enhancement in precipitation, causing an increasing in vegetation cover and favoring the growth of plants, while the weakened EASM intensity may result in a reduction of precipitation, accompanied by decreased vegetation cover and curbing the growth of plants. Considering the variations of synthesized fire activity and effective moisture evolution in eastern monsoonal China, the fuel biomass shall not be a constraining factor for fire activity in this region, whereas the most important controlling factor of fire activity in this study area should be moisture conditions (e.g., humid climate or high rainfall seasonality), particularly during the Holocene optimum (~9000–6000 cal yr BP, as defined by peak EASM precipitation). In fact, the relationships between climate and fire activity appear to vary between regions and still vary over time (Xue et al., 2015; Hawthorne and Mitchell, 2017), owing to the influence of local conditions. Our synthesis provides the evidence for better understanding the relations between climate and fire activity at a variety of geographical scales.

Notably, synthesized Holocene fire activity in the eastern monsoonal China is also apparently related to human history, represented by estimates of population and numbers of archaeological sites (see Figs. 4 and 5, Table 2). This indicates that Holocene fire activity in eastern monsoonal China may have been influenced by the human fire-use (e.g., forest clearance, land-use changes), especially as both population and the number of archaeological sites increased from the MH to LH. Humans can influence fire activities in several ways: by starting new ignitions, by changing fuel characteristics, by actively suppressing fires, etc. Given the long history of human occupation in China, including the traditional use of fire for agriculture and slash and burn practices, human activity could be reasonably assumed to play an important role in regulating fire activity in eastern monsoonal China from the MH to LH (e.g., Zhao et al., 2010; Tan et al., 2011; Wang et al., 2013). Our data show that fire increased concurrently with the number of archaeological sites and population in eastern monsoonal China from the mid- to late-Holocene (Figs. 4 and 5), possibly suggesting a close relation between fire activity and human impacts. In addition, fire activity in northern China varies more frequently than it does in southern China, which might be due to asynchronous patterns of human development (represented by the number and density of archaeological sites) between the northern and southern parts of China (Hosner et al., 2016; Wang et al., 2014). The first noticeable increase in archaeological site density occurred before ca. 8000 cal yr BP in northern China, while archaeological sites remained at low density for a much longer period in southern China (Fig. 5). Although the relationship between the presence of humans and fire history is not robustly evidenced before ca. 8000 cal yr BP, human impacts on fire activity cannot be totally ruled out. With the relatively coarse time-resolution of the series available at present, it is hard to disentangle a specific driving factor as the primary cause of fire activity in the past, and efforts are required to produce more high-resolution analyses of paleo-fire activity.

5.3. From fire activity to carbon release

Climate and humans both play a role in determining fire patterns, while fire also can influence the climate system via the release of carbon. The combustion of biomass leads to the release of carbon dioxide (CO_2), methane (CH_4), carbon monoxide (CO), and nitrous oxide (N_2O), as well as aerosols and particulates. These emissions, particularly CO_2 and CH_4, affect global climate because they are long-lived greenhouse gases (Harrison et al., 2010). To date, there is still a debate about the relation between global fires and atmospheric CO_2 concentration recorded in the Antarctic ice cores. Based on quantitative reconstructions of biomass burning deduced from stratified charcoal records from Europe, South-, Central- and North America, and Oceania, Carcaillet et al. (2002) found that global fire indices parallel the variation of atmospheric CO_2 concentration, and demonstrated that changes in fire regime may have affected global atmospheric CO_2 through the Holocene. That is, human fire-use has increased atmospheric CO_2 concentration since the mid-Holocene (about 7000 to 6000 years ago). Carcaillet et al. (2002) also deduced that fires from the high and middle latitudes of the Northern Hemisphere seemed to be a cause of global atmospheric carbon flux, while the effect of biomass burning on the carbon budget could be less important in low latitudes than in middle and high latitudes. However, Marlon et al. (2013) have recently synthesized more existing sedimentary charcoal records to reconstruct Holocene fire history at various scales (i.e., regional, continental and global), and suggest that, globally, the trends in fire history and greenhouse gases (e.g., CO_2, CH_4) inferred from the ice-core records are not similar, suggesting that factors other than fire, such as changes in peatlands or shallow water sedimentation of $CaCO_3$, are a more significant driver of centennial and millennial-scale variations in global atmospheric composition (Marlon et al., 2013). In fact, relations between biomass burning and carbon release may vary in different environments and at various spatial-temporal scales, due to the diversity of physical features (e.g., latitude, altitude, topography) and/or sensitivity to atmospheric circulation patterns, as well as other factors. Interestingly, the synthesized fire history record in eastern monsoonal China closely parallels global atmospheric CO_2 concentration from Antarctica (Monnin et al., 2004) during the Holocene (Fig. 6). A decrease in fire activity from 11,000 to 9500 cal yr BP corresponds to a decrease in CO_2 almost at the same time. The increasing fire activity starting around 7500 cal yr BP matches the rise of CO_2 closely near the same time, suggesting that the carbon released by fires to the atmosphere intensified from the MH to LH, i.e. during significant periods of agricultural development since about 8000 years ago in China. Carcaillet et al. (2002) once deduced that human-induced fires in different regions (e.g., eastern Asia, India and Africa) might explain the increasing atmospheric CO_2 concentrations recorded in Antarctica during the last 7000 years. Regardless of what controlled changes in fire regimes over the Holocene, the parallel trends in fire history and atmospheric CO_2 apparently demonstrate that changes in fire activity in eastern monsoonal China may play a role in the variation of global atmospheric composition at an orbital timescale, or that CO_2-driven EASM changes (Lu et al., 2013) may have affected fire history in eastern monsoonal China. Of course, it should be pointed out that calculating emissions from charcoal and/or other kinds of data (as representatives of fire activity) is particularly challenging (Marlon et al., 2013), and reliable quantitative estimations of carbon emissions resulting from paleofires are hardly possible at present (Carcaillet et al., 2002), due to

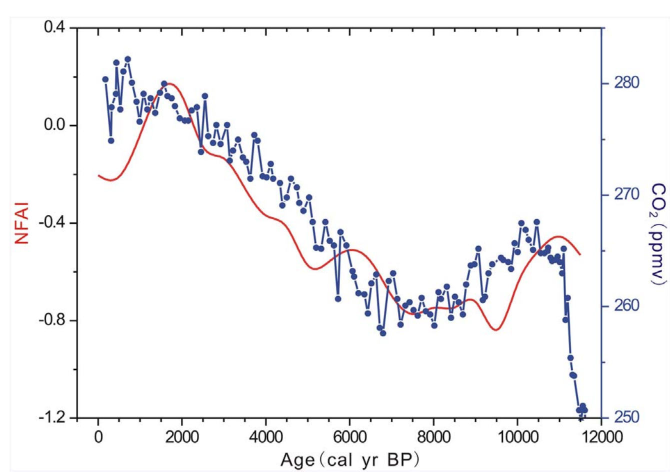

Fig. 6. Comparison of synthesized fire activity in eastern monsoonal China (this study) with the CO_2 concentration inferred from the Taylor Dome ice-core (Monnin et al., 2004). Here, it is assumed that a low normalized fire activity index corresponds to a low carbon-release resulting from a low fire activity, and vice versa for a high index.

the lack of more comprehensively and accurately mechanistic fire models evaluated against paleofire data. In any case, our results at least reveal an interesting relationship between fire activity (and then related carbon-release) in eastern monsoonal China and global atmospheric CO_2 concentration.

6. Conclusions

Through the combined analyses of fire indices from 14 localities, we have systematically reconstructed for the first time fire history for eastern monsoonal China during the Holocene, providing some insights into the long-term interconnectedness of fire activity, climate change, and human activities in this region. The synthesis curve for the monsoonal region of China as a whole shows that overall fire activity was higher during the early part of the EH, lower during the latter part of the EH and the MH, and increased towards the LH. The general pattern of fire history in eastern China closely follows the Holocene evolution of effective moisture in the monsoon-influenced region of China at an orbital timescale, i.e., more fires occurred during drier conditions, while less fire occurred during more humid conditions. Our results suggest that fire activity in eastern monsoonal China was primarily driven by climate changes (i.e., variations of past moisture conditions) and monsoon-related changes in vegetation communities, ultimately forced by the NHI on orbital timescales over the Holocene. Our data also show that fire activity increased concurrently with significant human development from the mid- to late-Holocene, suggesting a close relation between fire activity and human activities (human fire-use; e.g., forest clearance, land-use changes) since about 7500 years ago, although the relative impacts, and relationships between human population and activity and climate change is complex and difficult to disentangle. Moreover, fire history in eastern monsoonal China closely parallels global atmospheric CO_2 concentration from Antarctica during the Holocene, implying that changes in fire activity in eastern monsoonal China may play a role in the variation of global atmospheric composition, or that CO_2-driven climate changes may have affected fire history in eastern monsoonal China. As the spatial and temporal distribution of paleofire records included in our database is relatively sparse, and high-resolution paleofire records within eastern monsoonal China are limited, a denser network of sites with more precisely dated, high-resolution records is urgently needed. This will enable improved analysis of changes in fire activity and their relationships to climate and humans in the monsoonal region of China.

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